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A Numerical Study on Hydraulic Characteristics in the Ice Harbor-type Fishway

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Abstract

Recently various types of fishways have been developed and constructed in order to preserve diversity of fish species and restore the riverine ecological system. Some of the fishways in Korea, however, seem to be designed and installed without careful study on their functions and swimming characteristics of target fishes. The present study aims to elucidate proper hydraulic characteristics of the Ice Harbor-type fishway. In the present study, we analyzed the hydraulic characteristics depending on changes in the spans of walls in the Ice Harbor-type fishways, by using Flow-3D, a three dimensional numerical simulation program. Two physical experiments were performed to verify the results of the program. The comparison between the physical model and the numerical model showed that the results of the numerical model are in good agreement with the physical opponent. A series of numerical simulation were performed with various pool-aspect ratios (the ratio of span of fishway to its width). The numerical simulations revealed that, as the spans of baffles widens, the flow velocities of entire area decreases and the flow velocity of orifice area increases. The results showed that the pool aspect ratio should be larger than 1.0 to avoid the streaming flow, where fish could not ascend easily. As the ratio increases, the recirculation zone develops at the vertical plane and the flow condition becomes an inclined flow, which is the proper condition for fish ascending.

Keywords: *Ice Harbor-type fishway, hydraulic characteristic, fish movement, three dimensional numerical simulations*

1. Introduction

River crossing structures, such as dams, small dams and drop structures, in the rivers work as physical obstacles to keep fishes from migrating, disconnect the ecological linking, and result in reducing the species diversity and decreasing the numbers of a species (Baxter, 1977; Harris, 1984; Jacobs, 1990; Mallen-Cooper, 1995).

Recently, interest rising in river environments in Korea, much effort has been made to develop nature-friendly river environment. Constructing fishways in weirs and small dams in rivers is one of methods to preserve river ecology systems, sustaining the weir's flood control and water supply functions. Some of the fishways, however, have been designed improperly due to lack of indepth study on the hydraulic characteristics of themselves as well as swimming characteristics of the target fishes. They have been typically selected without sufficient investigation and testing, and in many cases their functions fail due to inappropriate management.

In order to maintain functions of fishways, it is most important to design them so that the resulting flow characteristics of them are proper for the target fishes to ascend easily. Understanding and estimating the hydraulic characteristics are prerequisite to make the optimal shapes of fishways. Most of the earlier studies of fishways have been focused on the flow structure by means of hydraulic models (Wu *et al*., 1999; Kim, 2001) and field observations (Izumi *et al*., 2000). Tsujimoto and Shimizu (1996) applied a numerical simulations based on k-ε turbulence model to flows in stream-type fishways: Denil type, superactive-type, bottom baffles and Alaska steep pass. Flow structures in pool-and-weir fishways were also investigated by Gotoh *et al.* (1999) using MPS (Moving Particle Semi-implicit method), by Maeno *et al.* (2001) and Namihira *et al.* (2006) using VOF (Volume of Fluid method) in generalized curvilinear coordinates. Fujihara (2000) developed a shallow water model using Godunov-type scheme on quad-tree grids and applied it for flows in vertical slot fishways (Fujihara *et al*., 2003) and in fishways with embedded stones (Fujihara and Chhatkuli, 2006). Lim *et al.* (2006) analyzed the three dimensional flow fields within the pools of vertical slot fishway, circulating flow and the development of turbulent flows around the structures. Various trials have been made to analyze the flow characteristics within the fishways through hydraulic experiments to design efficient fishways. Through the model test, however, it is not easy to elucidate the flow characteristics of the various shapes of fishways and select optimal configurations that are suitable for field conditions.

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Recently, therefore, many studies have been performed using three dimensional numerical models to analyze the flow characteristics within the fishways. Park (2007) analyzed the flow characteristics within the offset baffle type fishway with a three dimensional numerical simulation program and investigated the capability of three dimensional numerical modeling to design fishways. He showed that the numerical predictions of the velocity field are in good agreement with the experimental measurement. Using three dimensional numerical simulations, Ahn (2008) analyzed the flow characteristics in the fishway depending on the depth for the normal type, exit type and rest type. These studies demonstrated that three dimensional numerical model is a good practical tool to economically and efficiently design fishways. In Japan where the Ice Harbor-type fishway is one of the most popular fishways, numerical simulations of the fishway were performed with many researchers, including Hayahshida *et al.* (2000), Onitsuka *et al.* (2006) and Namihira (2009). Most of them, however, took only simple step-type fishway without notches and orifices in the baffles into account.

The present study is to analyze the flow characteristics in the Ice Harbor-type fishway via a three dimensional numerical modeling and present the hydraulic characteristics of such flows which guide us to find optimal configurations of the fishway.

2. Ice Harbor-type Fishway

2.1 Basic Structure

As shown at Fig. 1, the Ice Harbor-type fishway consists of overfall parts (notches) which has low rise on each side of walls, a non-overfall part (wall) in the center between the baffles, and openings (orifices) below the notches. Fig. 2 shows an example of the Ice Harbor-type fishway installed at a small weir. The non-overfall area in the center typically has a space in which the fish can take a rest during ascending. Orifices at the bottom side of overfall part might be helpful for the fishes living at the low and mid-level of depth to ascend. The design factors which should be taken into consideration in designing the Ice Harbor-type fishway include the span between the baffles (pool length, L), the gradient of the fishway ($\Delta H/\Delta L$), the width and arm's length of non overfall area, the height (H) of overfall area at both banks, the size and location of orifice, etc. In the present study, we analyzed one of them, the hydraulic characteristics within the pool and the flow patterns due to changes in the spans between the baffles. The changes in average velocity of overfall area and orifice area at both banks were analyzed. In the analysis, recirculating current (especially, clockwise recirculation at Fig. 3) within the pools was investigated. This recirculating current is a part of the streaming flow. Since the streaming flow confuses the ascending fish with the upstream direction and makes them lose their way, it should be avoided when we design the fishways.

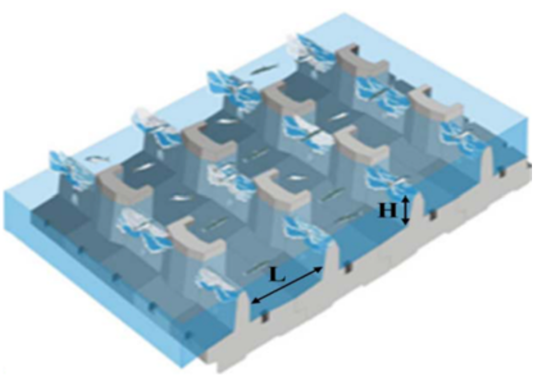


Fig. 1. Concept of the Ice Harbor-type Fishway

2.2 Flow Characteristics in Fishways

The flow characteristics in fishways should be proper for the target fish. In most fishways in Korea, the target fishes were not clearly specified. It means that most cases the fishways were improperly designed without considering how well the fishway would function (Park, 2007).

There are two important things in designing fishway in hydraulic point of view. One thing is the maximum flow velocity in fishway should be smaller than the burst swim speed of the target fish, and the other is that the flow pattern in the fishway should work proper for the fish to ascend the fishway.

The former is rather easy to check up, because it is commonly well documented in fishway design manuals. If we select sweetfish as the target fish of the fishway, the maximum flow velocity in the fishway should be less than 1.78 m/s, busting swimming speed of sweetfish (Park, 2007). For the latter, it is not trivial to figure out, since the flow pattern may significantly vary according to minor change of fishway configurations.

In that regard, Clay (1961) classified the flow patterns in step type fishway, including pool and baffle type and the Ice Harbor-

Fig. 2. Ice Harbor-type Fishway Installated at a Small Weir

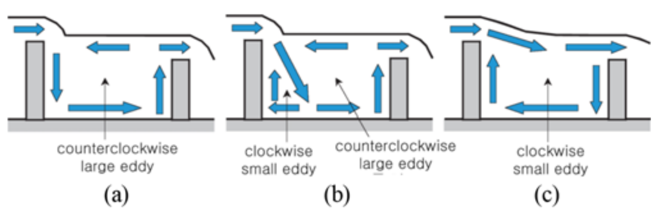


Fig. 3. Flow Patterns in Fishways (Hayashida *et al.*, 2000): (a) Plunging Flow, (b) Inclined Flow, (c) Streaming Flow

type, into two classes; plunging flow and streaming flow. Hayashida *et al.* (2000) added one more pattern, inclined flow, between Clay's flow patterns. Fig. 3 shows the flow patterns at step type fishway. Among them the plunging flow is the proper flow pattern which fish can ascend easily through the baffles, and the streaming flow should be avoided. In the streaming flow, fish often lost upstream direction and fails to ascend.

It is expected that the flow pattern would changes from a streaming flow to a plunging flow, as the pool aspect ratio, defined as the ratio of span of fishway to its width, decreases. Therefore, from the flow pattern we can figure out the minimum pool aspect ratio in which the flow pattern remains in plunging flow condition. The maximum pool aspect ratio cannot be determined with such a manner. If the pool aspect ratio increases, the total length of the fishway will be increased. It means that the maximum ratio would be determined by geometric or economic matter.

One thing to be noticed is that the above classification was for the baffle type fishway without orifices. Fishways having orifices like the Ice Harbor-type fishway may need a little different flow classification. Unfortunately, no study has done on such classification for flows in the Ice Harbor-type fishway.

2.3 Verification of Numerical Model

To investigate the numerical model performance in calculating the flow characteristics in the fishway, some measured data are need. For the observed data, two hydraulic experiments were performed in a laboratory. The pool aspect ratios of two cases were 0.5 (Fig. 4a) and 1.0 (Fig. 4b), respectively. The hydraulic experiments were done in the experimental flume of 0.8 m (B) × 0.8 m (H) × 25 m (L). The model fishways have a total of five baffles. Representative hydraulic characteristics between the baffles were measured for the span between the second and fourth baffles (at Figs. 4a and 4b, red boxed region), which seemed not to be affected by upstream and downstream conditions. As shown in Table 1, however, flow fields observed in the first and second pools are slightly different from each other. It means that the flow is still developing across pools in streamwise direction and can be slightly sensitive to the upstream and downstream flow conditions.

A three dimensional electronic velocimeter, KENEK VP3000, was used to measure the flow velocity. Measurement accuracy of velocimeter was ±0.01 m/s.

As shown in Fig. 5, the width of overfall area (notches) is set equal to that of non-overfall area (wall), and the hole (orifices) with the diameter of B/13 are installed near the bottom at the center of both banks and the side walls. At a discharge of 60.84 L/s, the approaching velocity is 0.2 m/s and the depth at the upstream and downstream boundary are 0.3 m and 0.05 m, respectively. Since the flow velocity covers a wide range, it is hard to say a representative Froude number. For the case that the approaching velocity was 0.23 m/s, the overall Froude number

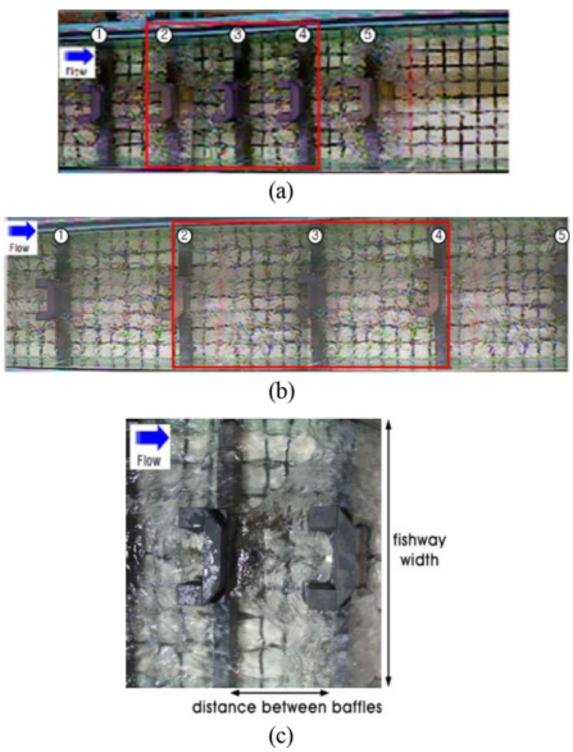


Fig. 4. Hydraulic Experiments of Ice Habor-type Fishways: (a) Pool Aspect Ratio : 0.5, (b) Pool Aspect Ratio : 1.0, (c) Flow Pattern Around a Baffle

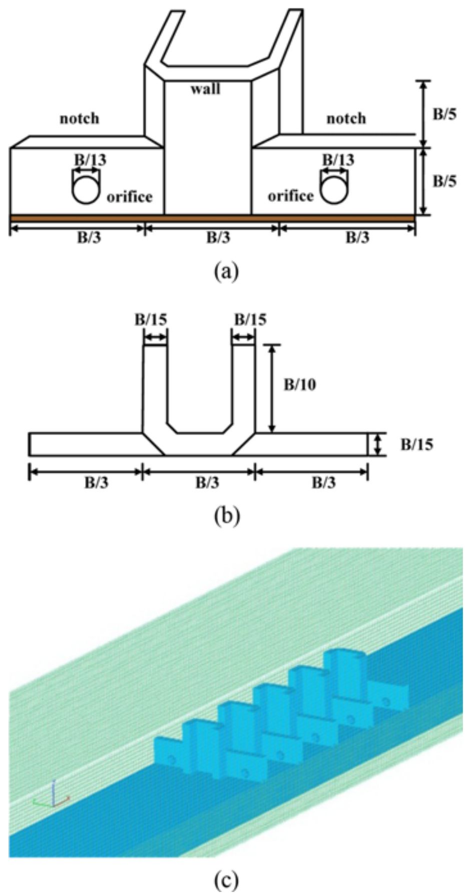


Fig. 5. Ice Habor-type Fishway Model: (a) Cross Section, (b) Plan View, (c) Computational Mesh (Part)

was 0.58.

For three dimensional numerical simulations, we used FLOW-3D model. As shown in Fig. 5(c), the simulation mesh consists of 264,000 grid points with 200 for x-axis, 120 for y-axis, and 11 for z-axis. We use the physical inputs of 0.001 Pa·s for viscosity, 1,000 kg/m^3 for density and 0.013 for roughness. For calculation of turbulent flow, RNG k-ε model was selected with wall functions for solid boundaries.

The results of the numerical model were compared with those of the hydraulic experiments. For pool aspect ratio 0.5 and 1.0, we compare the flow velocity fields at notches and orifice areas. As shown in Table 1, the results of correction and calibration of three dimensional numerical simulation showed that the flow velocity (V_o) of the overfall area has the maximum error rate of 5.0% and that the flow velocity (V_h) of the orifice area has the maximum error rate of 8.2%. The maximum error rate was defined as the maximum difference between the calculated velocity and the observed velocity divided by the calculated one. These results agree with those of hydraulic experiment to a great extent. When the flow duration in the pool is checked, it is found that the patterns of the recirculation flows are almost similar.

For further quantitative evaluation, modeling efficiency (EF) is introduced. The EF value is defined as follows (Fujihara *et al.*, 2009):

$$EF = \frac{\Sigma_{i=1}^{n}(h_o-\overline{h_o})_i^2 - \Sigma_{i=1}^{n}(h_c-h_o)_i^2}{\Sigma_{i=1}^{n}(h_o-\overline{h_o})_i^2} \quad (1)$$

where h_o is the observed value, h_c the calculated value, n the number of data, and $\overline{h_o}$ the average of the observed value.

Table 2. Modeling Efficiency

Pool aspect ratio	u	v	w	Velocity magnitude
0.5	0.932	0.336	0.268	0.727

The averaged values of three velocity components and the magnitude of velocity are shown at Table 2. Table 2 shows that the calculated longitudinal velocity u and the magnitude of velocity are fairly good agreement with the observed ones, while the other two velocity components showed relatively poor agreement. Very similar results were found by Fujihara *et al.* (2009).

The analysis showed that FLOW-3D could simulate the flow pattern in the Ice Harbor-type fishway and it could be used for the preliminary design purpose.

3. Numerical Simulation for Fishway Design

3.1 Test Cases

We carried out seven computations with varying the pool aspect ratio to 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0 as the condition for three dimensional numerical simulation to show the effect of the pool lengths on the hydraulic characteristics in the Ice Harbor-type fishway (see Table 3). Because the approach velocity changes as the pool aspect ratio changes under the same upstream discharge condition, we perform six analyses by

Table 1. Comparison of Experimental Measurements and nUmerical Predictions

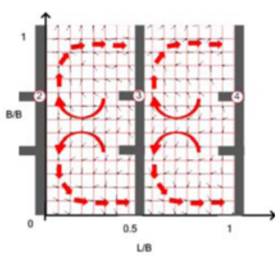
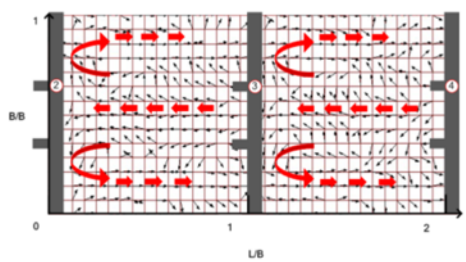
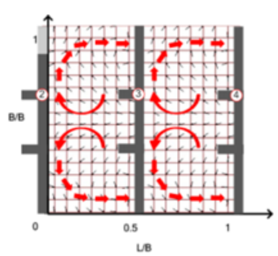
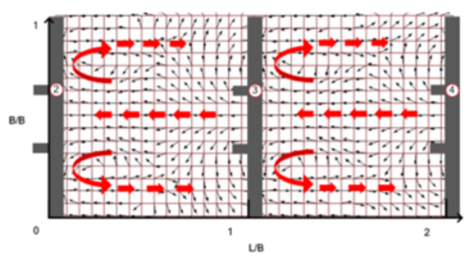
<table>
<tr><th></th><th>Pool aspect ratio 0.5</th><th>Pool aspect ratio 1.0</th></tr>
<tr><td rowspan="4">Physical model</td><td>
</td><td>
</td></tr>
<tr><td>V_o= 0.930 m/s</td><td>V_o = 1.080 m/s</td></tr>
<tr><td>V_h = 0.690 m/s</td><td>V_h = 0.570 m/s</td></tr>
<tr><td>h = 0.280 m</td><td>h = 0.270 m</td></tr>
<tr><td rowspan="4">Numerical model</td><td>
</td><td>
</td></tr>
<tr><td>V_o = 0.930 m/s</td><td>V_o = 1.031 m/s</td></tr>
<tr><td>V_h = 0.743 m/s</td><td>V_h = 0.523 m/s</td></tr>
<tr><td>h = 0.278 m</td><td>h = 0.265 m</td></tr>
</table>

Table 3. Numerical Simulation Conditions

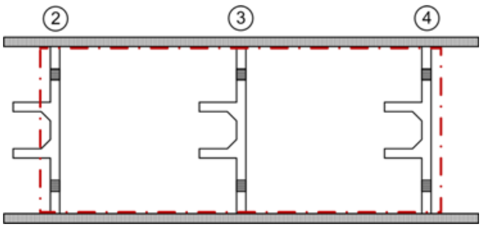
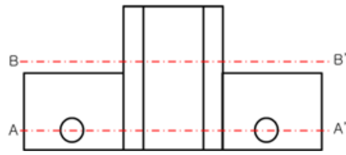
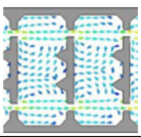
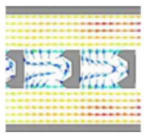
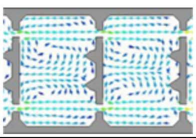
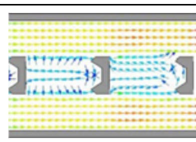
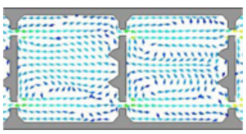
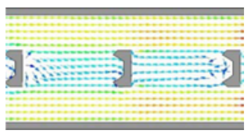
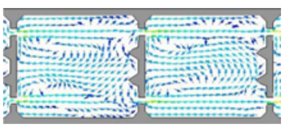
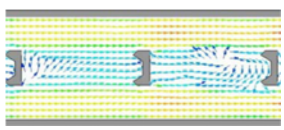
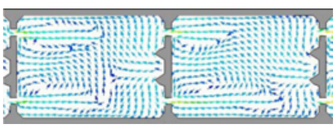
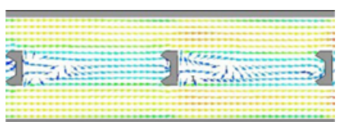
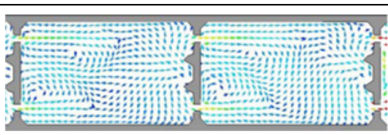
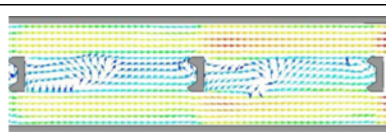
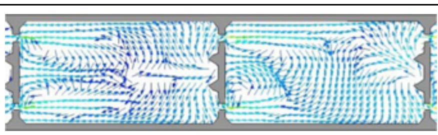
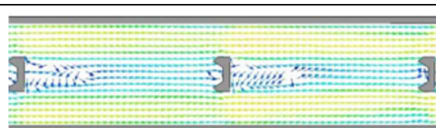
Run no.	Pool aspect ratio	Upstream		Downstream water depth (m)
		Velocity (m/s)	Water depth (m)	
1	0.50	0.171	0.278	0.035
2	0.75	0.170	0.285	0.038
3	1.00	0.166	0.293	0.040
4	1.25	0.165	0.297	0.040
5	1.50	0.163	0.300	0.040
6	1.75	0.163	0.310	0.045
7	2.00	0.160	0.315	0.050

varying the flow velocity to 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 with reference to and checking approach velocities of each pool aspect ratio before the Ice Harbor-type is constructed. For the analysis of hydraulic characteristics of Ice Harbor-type fishway we also check the average flow velocities and flow duration at the pool in the overfall area and orifice area as the path for ascending fishes.

3.2 Maximum Velocity

Table 4 shows the velocity distribution at the x-y planes of z = 0.05 m (crossing the orifice centers), and z = 0.22 m near the free surface. As we expected, overall magnitude of velocity is large at the plane near the free surface than near the bottom. Downstream of non-overfall (wall) areas show clearly slower velocity distributions and a couple of pairs of and a pair of recirculation zones at the planes cross the orifice and near free surface, respectively. It would help for fish to take a rest during ascending.

Table 4. Velocity Distribution at Selected Horizontal Planes

		 section location  velocity magnitude
Pool aspect ratio	A-A' (5 cm) section	B-B' (22 cm, surface) section
0.50		
0.75		
1.00		
1.25		
1.50		
1.75		
2.00		

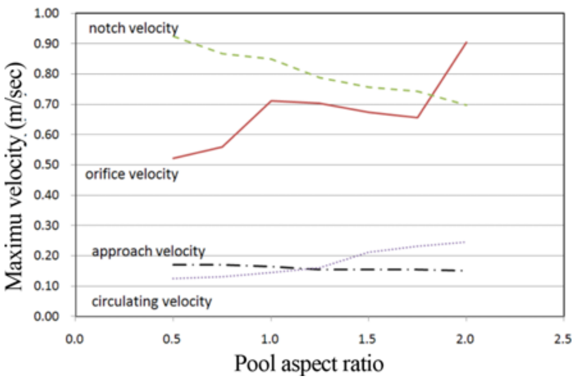


Fig. 6. Maximum Velocity Variation

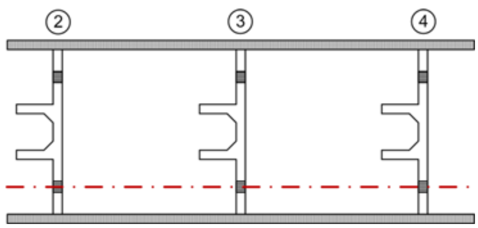
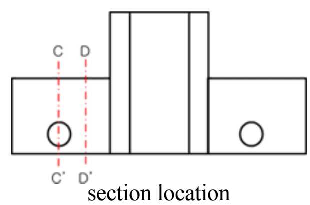
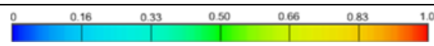
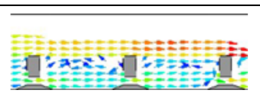
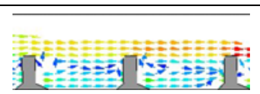
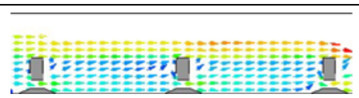
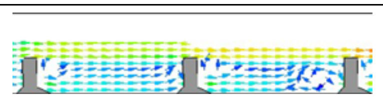
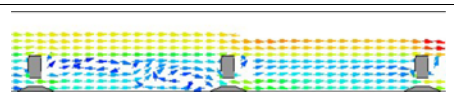
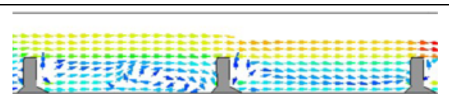
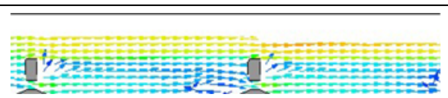
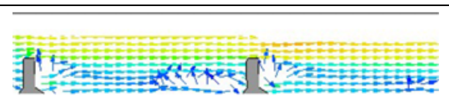
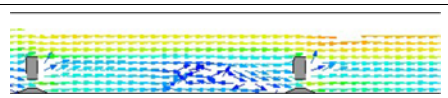
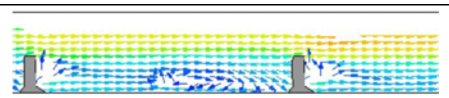
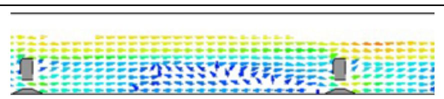
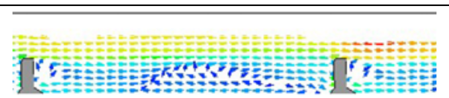
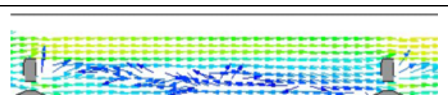
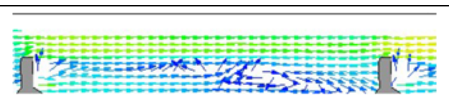
Figure 6 shows maximum velocity variation for the seven cases. This figure shows that the maximum velocity decreases at the notch and increases at the orifice, as the pool aspect ratio increases. These results are fundamentally usable to determine the fishway configurations that is suitable for any specific target fish.

3.3 Flow Pattern

Another important thing to be checked is flow pattern in vertical plane. As mentioned at the previous section (2.2 Flow Characteristics for Proper Fishway), it is recommended to avoid a streaming flow in the pool area. Table 5 shows the velocity distribution at the vertical (x-z) planes crossing the orifice and overfall section. The table also shows that the flow condition becomes the streaming flow, as the pool aspect ratio is less than 1.0. It means that the pool aspect ratio should be larger than 1.0 to avoid the streaming flow in the pool. As the aspect ratio is larger than 1.0, a recirculation zone develops at the vertical plane and the flow condition becomes an inclined flow as shown at Table 5. As the ratio increases, the recirculation flows were clearly developed.

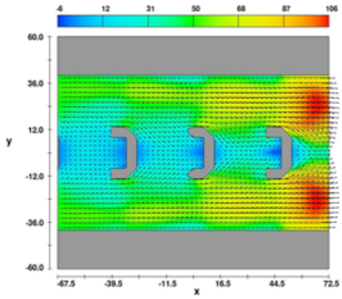
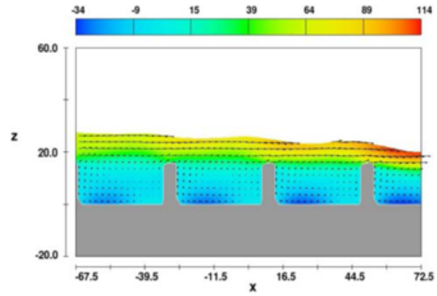
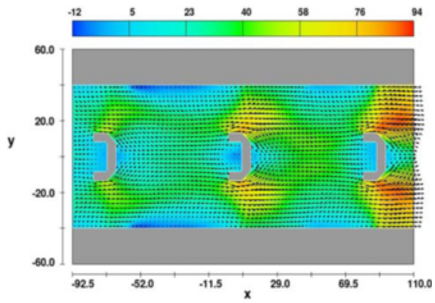
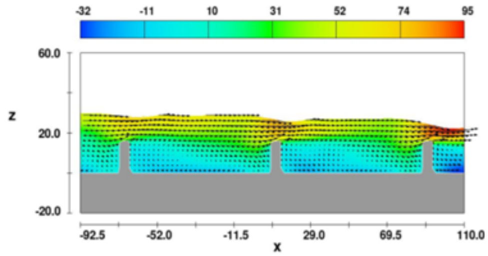
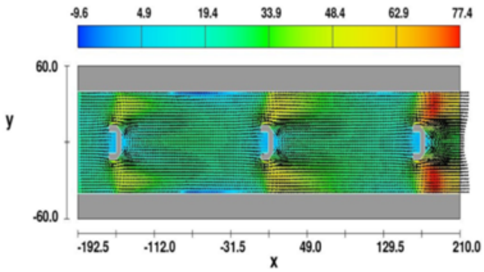
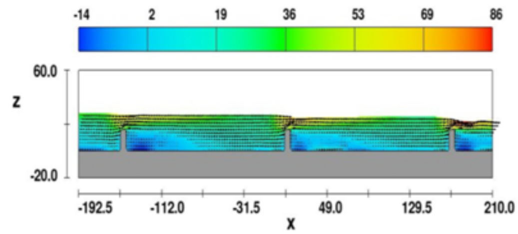
Additional three numerical simulations were carried out on further refined grids to reproduce flow patterns at higher resolutions. Table 6 shows the velocity distribution at selected horizontal and vertical planes for the cases that the pool aspect ratios of 0.5, 1.0 and 2.0. It is clearly visible at figures in Table 6 that, as the aspect ratio increases, the flow pattern changes from

Table 5. Velocity Distribution at Selected Vertical Planes

		 section location  velocity magnitude
Pool aspect ratio	C-C' (orifice) section	D-D' (overfall) section
0.50		
0.75		
1.00		
1.25		
1.50		
1.75		
2.00		

NOTE: for Ra = 1.25~20, right side of the figures were truncated.

Table 6. Detailed Velocity Distribution at Selected Horizontal and Vertical Planes

Pool aspect ratio	Horizontal plane (surface)	Vertical plane (ovefall)
0.50		
1.00		
2.00		

the streaming flows to the inclined flows at the vertical planes. This result confirms the previously mentioned finding that the aspect ratio should be larger than 1.0 to avoid the development of the streaming flow in the pool.

4. Conclusions

In the present study we investigated the flow characteristics in the Ice Harbor-type fishways. A series of numerical simulations were carried out using the Flow-3D, a three dimensional numerical simulations program for various values of the pool aspect ratio.

For the test of the applicability of the Flow-3D, the maximum error rate of the flow velocity (V_o) of the overfall area reached about 5.0%, and that of the orifice area (V_h) was about 8.2%, and such results were in good agreement with the hydraulic experiment data. The analysis showed that FLOW-3D could simulate the flow pattern in the Ice Harbor-type fishway and it could be used for the preliminary design purpose.

The analysis of hydraulic characteristics depending on the change in the span between the baffles in the Ice Harbor-type fishway shows that the flow velocity in the overfall (notch) areas increases as the pool aspect ratio in the pool decreases and that the flow velocity in the orifice area decreases as the pool aspect ratio in the pool decreases. This is because the flow velocity in the overfall area increases and the flow velocity in the orifice area arises relatively less as the flow resistance due to the recirculating flow decreases when the span between the baffles is narrow.

The calculated results showed that the flow condition becomes the streaming flow, as the pool aspect ratio is less than 1.0. It means that the pool aspect ratio should be larger than 1.0 to avoid the streaming flow in the pool. As the aspect ratio is larger than 1.0, a recirculation zone develops at the vertical plane and the flow condition becomes an inclined flow. As the ratio increases, the recirculation flows were clearly developed.

The present study shows that the analysis using Flow-3D for the flow characteristics in the fishway can be applied at the stage of pretesting in constructing the fishways and the analysis using Flow-3D will be useful in designing the Ice Harbor-type fishway in the future.

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